Application of Deep Convective Cloud Albedo Observation to Satellite-Based Study of the Terrestrial Atmosphere: Monitoring the Stability of Spaceborne Measurements and Assessing Absorption Anomaly

Yongxiang Hu, Bruce A. Wielicki, Ping Yang, Paul W. Stackhouse, Jr., Bin Lin, and David F. Young

***Abstract*—An objective method is developed to monitor the stability of spaceborne instruments, aimed at distinguishing climate trend from instrument drift in satellite-based climate observation records. This method is based on four-years of Clouds and the Earth's Radiant Energy System (CERES) broadband observations of deep convective cloud systems with cloud-top temperature lower than 205 K and with large optical depths. The implementation of this method to the CERES instrument stability analysis reveals that the monthly albedo distributions are practically the same for deep convective clouds with CERES measurements acquired from both the Tropical Rainfall Measuring Mission and Terra satellite platforms, indicating that CERES instruments are well calibrated and stable during both missions. Furthermore, with a nonlinear regression neural network narrowband–broadband conversion, this instrument-stability monitoring method can also be applied to narrowband instruments such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Visible Infrared Scanner (VIRS). The results show that the drifts associated with both VIRS and MODIS instruments are less than 1% during a four-year period. Since the CERES albedo measurements are highly accurate, the absorptance of these opaque clouds can be reliably estimated. The absorptions of these clouds from observations are around 25%, whereas the absorptions from theory can be as low as 18%, depending on ice cloud microphysics.**

***Index Terms*—Absorption anomaly, albedo, deep convective cloud, instrument stability, radiative transfer.**

I. Introduction

MONITORING the change of radiative energy budget at the top of the atmosphere (TOA) requires satellite measurements with durable instrument stability and reliable accuracy. With climate monitoring in mind, improving instrument stability has been one of the most important objectives of the Clouds and the Earth's Radiant Energy System (CERES) instrument designs, as articulated by Wielicki *et al.* [1]. In practice, the stability of a spaceborne instrument can be objectively assessed by investigating the albedo distributions derived from the measurements of well-defined atmospheric objects. The availability of CERES broadband observation and Visible Infrared Scanner (VIRS) and Moderate Resolution Imaging Spectroradiometer (MODIS) narrowband observations from the Tropical Rainfall Measuring Mission (TRMM) and Terra platforms provides an unprecedented opportunity to investigate the month-to-month stability of both narrowband and broadband instruments by studying the albedo distributions of deep convective clouds.

Solar radiation measurements suggest that clouds absorb more solar radiation in comparison with the simulations based on the general climate models (GCMs), a phenomenon known as the cloud absorption anomaly [2]–[7]. There has been considerable debate on the magnitude of the discrepancy between observations and model calculations of cloud absorption. With accurate anisotropy models suitable for deep convective cloud systems and multiangle CERES measurements, the TOA albedos can be accurately measured. Additionally, the absorption of the deep convective clouds with very low transmissivity can be reasonably estimated. The shortwave absorptions of deep convective clouds with large cloud optical depths and very low cloud-top temperatures can be estimated from the accurate albedo measurements and compared with theoretical calculations for understanding the cloud absorption anomaly.

The intent of this paper is to assess the stability of the CERES instrument. Additionally, we wish to address the issue related to the cloud absorption anomaly, i.e., the discrepancy between the observed cloud absorption and corresponding model simulations. Furthermore, this paper also intends to provide an objective stability analysis of a narrowband instrument, such as MODIS, in terms of energy budget. A neural network model is developed on the basis of the conversion of MODIS narrowband radiances to CERES broadband radiances. Collocated MODIS and CERES cross-track-scanning mode data are used for training the multilevel nonlinear kernel regression neural network model with special noise handling characteristics. Other information, such as theoretical radiative transfer calculations,

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are adopted for improving the design of the neural network model as well as filling missing data at certain viewing angular geometry. Then, we study the monthly albedo distributions derived from the narrowband–broadband conversion. Compared with computing radiative fluxes from cloud retrievals from the conventional narrowband measurements, the neural network narrowband–broadband conversion has an advantage of by-passing various assumptions in the atmospheric retrievals as well as redundant theoretical calculations.

II. Albedo Distributions of Deep Convective Clouds and Implications on Absorption Anomaly

CERES measures broadband reflected solar radiation and infrared thermal emission. Unlike narrowband measurements such as VIRS and MODIS with cross-tracking scanning, CERES operates in both fixed-azimuth (cross-track) and rotational azimuth scanning modes. The CERES rotational-azimuth-scanning-mode measurements provide all possible azimuth angle coverage over a long time period and, thus, provide the anisotropy (radiance–flux relation) as well as albedo. Mathematically, the planetary albedo (α_p) that is solar zenith independent can be derived from cross-track radiance measurements as follows:

$$\alpha_P = \frac{\pi I(\mu_0,\mu,\phi)}{\mu_0 F_0 R(\mu_0,\mu,\phi) D(\mu_0)} \tag{1a}$$

$$R(\mu_0,\mu,\phi) = \frac{\pi \overline{I}(\mu_0,\mu,\phi)}{\overline{F}(\mu_0)} \tag{1b}$$

$$D(\mu_0) = \frac{\overline{F}(\mu_0)}{\int_0^{\pi/2} \overline{F}(\mu')\mu' d\mu'} \tag{1c}$$

where I is the CERES measured radiance, μ_0 is the cosine of solar zenith angle, F_0 is the solar irradiance at TOA, R is the anisotropy factor, and D is the solar zenith dependence of albedo for a specific object, such as deep convective clouds. $\overline{I}$ and $\overline{F}$ are broadband radiance and flux from long-term CERES measurements for deep convective clouds. $\overline{F}$ is calculated with CERES rotational azimuth scanning broadband radiance measurements $\overline{I}$ from every viewing geometry. Unlike albedo, $\pi I(\mu_0,\mu,\phi)/\mu_0 F_0 R(\mu_0,\mu,\phi)$, which is solar zenith angle dependent, planetary albedo is independent of solar zenith angle. Compared with albedo distributions, the monthly planetary albedo distributions have less bias from monthly dependence of solar zenith angles and, thus, smaller variances in comparison with albedo distributions, and thus they have less uncertainty for the purposes of monthly instrument stability studies.

The clouds considered in this paper are the cold and thick deep convective cloud systems. The criteria for the selection of these cloud systems are somewhat arbitrary. Here, we selected the clouds with cloud-top temperature colder than 205 K. The optical depths for these clouds are most likely greater than 100. The planetary albedo distribution of these clouds is peaked at 0.75 with small variances, as evident from Fig. 1. The variances are results of uncertainties in anisotropy models, cloud three-dimensional structures, and opacity. The tops of these clouds are quite high (> 10 km) in the atmosphere, and the gas absorptions of solar radiation above them are relatively small. The monthly and seasonal changes of the gas absorptions do not affect the

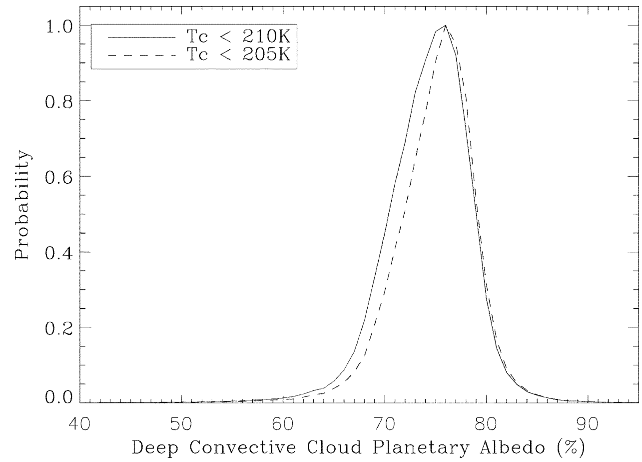

Fig. 1. Deep convective cloud systems albedo distributions for various cloud-top temperatures Tc.

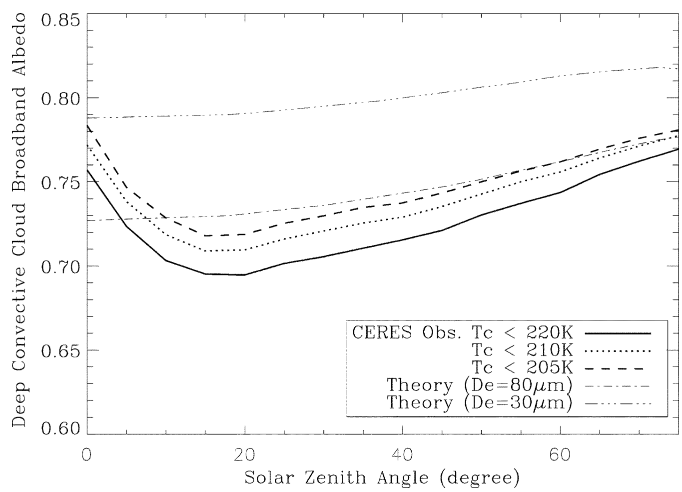

Fig. 2. Deep convective cloud albedo. Observations versus theory.

albedo distributions significantly. The deep convective cloud system reflects most sunlight and absorbs some solar radiation at near-infrared wavelengths. The cloud microphysical properties, which determine the amount of near-infrared absorptions, do not change from month to month. It is expected that the albedo distributions of these clouds are the same from month to month. Thus, we can monitor instrument stability by comparing the monthly albedo distributions. Fig. 2 shows that for the coldest and thickest clouds (Tc $<$ 220 K and opaque), the albedos approach 75% (dashed line) and are solar zenith angle dependent.

The cloud absorptances are essentially 1 minus albedo in these cases, since the transmittances are very close to zero. The dashed–dotted lines in Fig. 2 are albedos from theoretical radiative transfer calculations [8], [9]. In the present light scattering and radiative transfer calculation, nonspherical hydrometeors in the atmospheres are assumed to be aggregate ice crystals. Larger cloud particles absorb more solar radiation at near-infrared wavelengths because they scatter photons more strongly in the forward direction. This implies that a photon must be scattered many times before it can bounce back to space, and this increases the probability of photon absorption, which is directly proportional to the number of scattering events. For an optical depth of 100 or larger, ice clouds composed of aggregates with an effective size of 30 μm absorb about 18% of solar radiation,

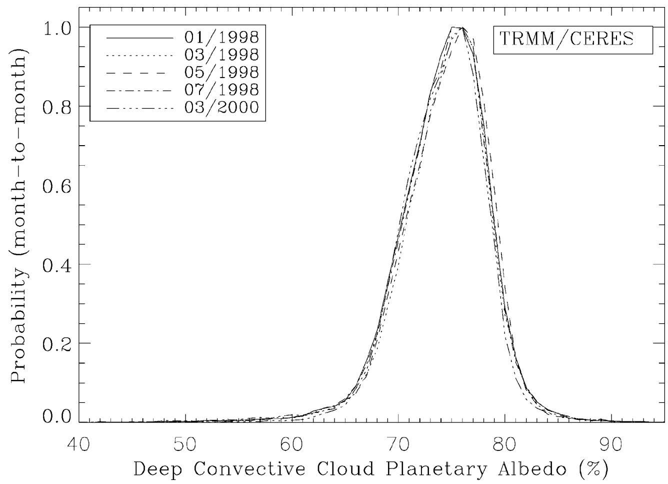

Fig. 3. TRMM/CERES monthly deep convective cloud albedo distributions.

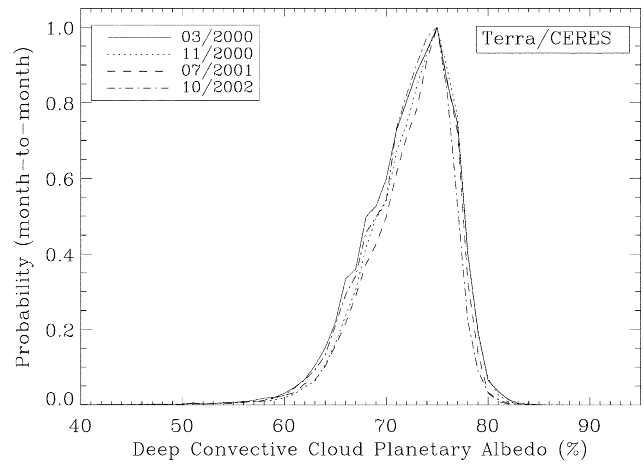

Fig. 4. Terra/CERES monthly deep convective cloud albedo distributions.

whereas the ones with 80-μm diameter absorb 25% of the total solar radiation.

It is possible to find ice particle microphysical properties that produce similar albedo (and thus absorption) to the ones derived from CERES observations if an effective ice particle size of 80 μm is representative for these clouds (Fig. 2). Since most of scattering happens in the upper part of the convective clouds where smaller particles (e.g., 30-μm effective diameter) dominate (Fig. 2, dashed–triple–dotted line) [12], the theoretical albedo can be up to 7% higher than the observations. In terms of absorption, the theoretical absorption value can be somewhere between 18% and 25%, while the absorption is around 25% from observations. There are significant differences in the solar zenith dependence of the albedos between theory and observations, especially for the overhead sun. This difference is possibly caused by particle orientations or three-dimensional effects and deserves a further study. Note that the effect of preferred orientations of nonspherical hydrometers on atmospheric radiative transfer is currently a hot research topic in scattering theory, radiative transfer, and remote sensing implementation.

III. Monthly CERES Broadband Deep Convective Cloud Albedo Distributions and Implications on CERES Instrument Stability

As a new generation instrument for monitoring earth's radiative energy budget [1], CERES started collecting data in 1998 onboard the TRMM satellite. While the global radiative energy budget observations recorded a changing climate in the past decades, it is important to know how much of the change is real and how much of it is attributed to instrument degradation [10]. This paper intends to establish a method for providing independent assessment. If the CERES instrument calibration drifted from month to month for some reason, it would be reflected in the monthly deep convective albedo distributions. Fig. 3 shows that the albedo distributions for these clouds are indeed the same from month to month. The shapes of the distributions are close to the Gaussian function, except for longer tails at the low albedo end because of the inclusion of some thinner clouds included. The albedo distributions shown in Fig. 3 indicate that the CERES instrument on the TRMM satellite has been quite stable during the time period. Additionally, the results shown in Fig. 3 imply that this present method for calculating the cloud albedo makes correct assumptions about cloud microphysics and solar zenith angle dependence.

After the TRMM mission, the CERES instruments onboard the Terra and Aqua satellites have continued data collection. Although TRMM and Terra have quite different orbits, Fig. 4 shows that the CERES deep convective cloud albedo distributions from the Terra mission are similar to the ones from TRMM. The shapes of the distributions are slightly different, and the variances of these distribution functions are slightly larger. The adoption of TRMM/CERES anisotropy and albedo-solar zenith angle dependence relations probably introduced some errors in the planetary albedo. These errors have similar impact on all months. The distributions from month to month are almost identical, indicating that the CERES instruments have been very stable since 2000.

IV. Narrowband–Broadband Conversion With Neural Network Models

It is difficult to derive accurate narrowband albedos directly from observations because the anisotropy information from narrowband observations is not available. Most narrowband observations are cross-track or along-track, and the observations are highly weighted at a few specific viewing azimuth angles. The CERES rotational azimuth scanning operation can only provide broadband anisotropy. To take the advantage of the CERES broadband anisotropy measurements and perform narrowband instrument stability analysis, we can convert narrowband reflectance to broadband reflectance, derive the equivalent broadband albedo using the observed CERES anisotropy information, and study the patterns of deep convective cloud albedo distributions. The most relevant narrowband information to the broadband shortwave fluxes includes: 1) a visible channel, which indicates cloud optical thickness; 2) a near-infrared channel, which indicates effective cloud particle sizes; and 3) a longwave window channel for cloud temperature. A visible channel is available both for VIRS and MODIS. The near-infrared channel at 3.7-μm wavelength and the window channel at 11 μm are also available on both instruments. Thus,

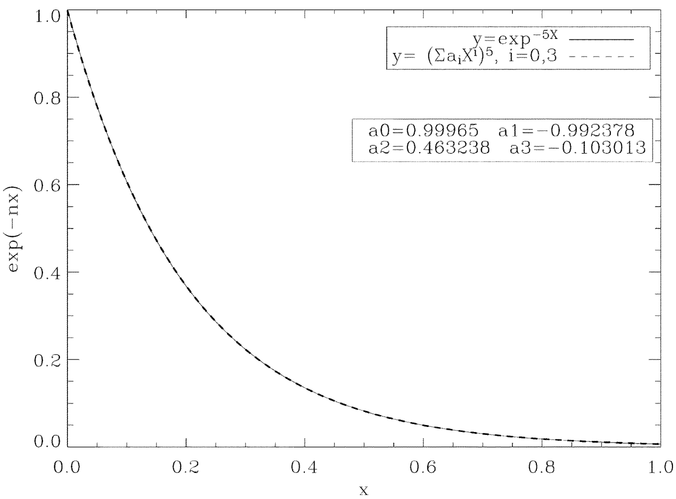

Fig. 5. Speedup exponential computation with polynomial fits.

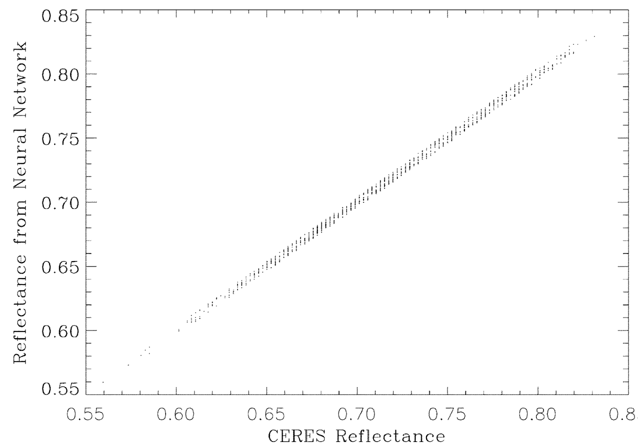

Fig. 6. Comparison of CERES broadband observations with neural network model narrowband–broadband conversion results using MODIS narrowband observations as inputs.

we will use these three narrowband channels as narrowband inputs.

To perform the narrowband–broadband conversions, we also need to know the geometry of the satellite and the sun. Such information includes solar zenith angle, viewing zenith angle, and relative azimuth angle. The output, broadband radiative fluxes, information comes from CERES shortwave (0.3–4 μm), and longwave (4–100 μm) observations. With a processing orbit, TRMM provides us nine-month collocated narrowband (VIRS) and broadband (CERES) observations at a wide variety of viewing geometries. Theoretical narrowband calculations are performed at large viewing angles, since such observations are not available. These data are adopted in our study as the training samples.

A generalized regression neural network model (GRNN) [13] is developed for the narrowband–broadband conversions. GRNN is a Nadaraya–Watson nonlinear kernel regression. Mathematically, the approach is similar to previous linear narrowband–broadband conversion studies [11] but more accurate. The analytic functional form is replaced by the neural network functional approximation in this paper.

The GRNN method is a normalized radial basis function (RBF) network, in which there is a hidden unit centered at every training case. These RBF units are called "kernels" and are usually probability density functions such as the Gaussian function. The hidden-to-output weights are just the target values, so the output is simply a weighted average of the target values of training cases close to the given input case. The only weights that need to be learned are the widths of the RBF units. GRNN is a universal approximation for smooth functions, so it should be able to solve any smooth function-approximation problem given enough data. By comparing with back propagating neural networks, GRNN can be trained instantaneously. But it requires more computations when applying it. After the GRNN is trained from TRMM/VIRS and TRMM/CERES data, we applied the neural net to Terra/MODIS narrowband data. Implementing the Nadaraya–Watson kernel regression can be very time-consuming because the kernel functions are exponential functions. The exponential functions are replaced by polynomials, which are computationally very fast. Fig. 5 shows that the fitted polynomial function is identical to the exponential function.

The broadband reflectances derived from the narrowband to broadband conversion using MODIS observations as inputs are compared with the broadband reflectances from CERES observations. Fig. 6 shows that the reflectances of deep convective clouds (Tc $<$ 205 K) derived from narrowband to broadband conversion using MODIS data as inputs matches the reflectances from Terra/CERES broadband observations.

V. Monthly Deep Convective Cloud Albedo Distributions Derived From VIRS and MODIS and Implications on VIRS and MODIS Instrument Stability

Using VIRS narrowband observations as inputs for the neural network narrowband–broadband conversions, we can derive VIRS "equivalent" broadband reflectances. Applying the same neural nets derived from narrowband–broadband conversion to the MODIS data, we can also derive the equivalent broadband planetary albedos for all MODIS measurements. As the narrowband-to-broadband conversion is derived from VIRS–CERES pairs, a small adjustment has to be made in order to account for the difference in solar constants of the visible channels (VIRS at 0.63 μm; MODIS at 0.65 μm) between the two instruments. The solar constants of the two visible channels differ approximately by 4%. Using the neural-network-derived broadband reflectance with the broadband anisotropy information from CERES observations and the albedo-solar zenith angle dependence, an equivalent CERES broadband albedo is derived for each VIRS or MODIS measurement.
Fig. 7 (VIRS) and Fig. 8 (MODIS) shows that there are no substantial drifts in the monthly albedo distributions for the deep convective clouds. The distributions from month to month have similar shapes and peak values. The equivalent broadband albedo distributions of five months (January 1998, March 1998, May 1998, July 1998, and March 2000) derived from VIRS narrowband-to-broadband conversion are almost the same (Fig. 7). The peak albedos of these five months are at 0.75. The distributions are not as perfectly Gaussian-like as the CERES monthly distributions are. And the variances are slightly larger, probably because of the errors in the narrowband–broadband

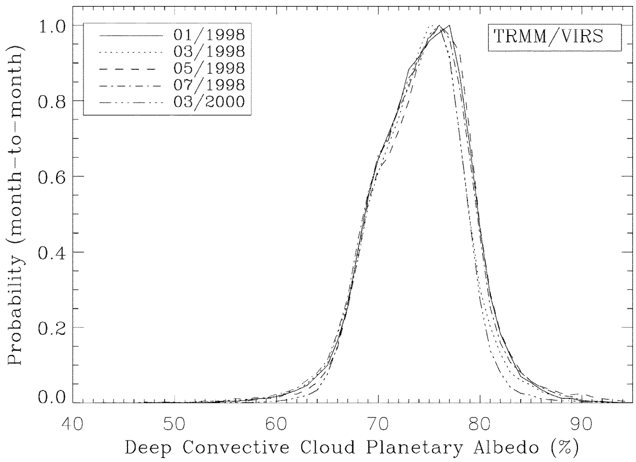

Fig. 7. VIRS stability studies using monthly broadband albedo distributions derived from narrowband-to-broadband conversions using VIRS narrowband observations as inputs.

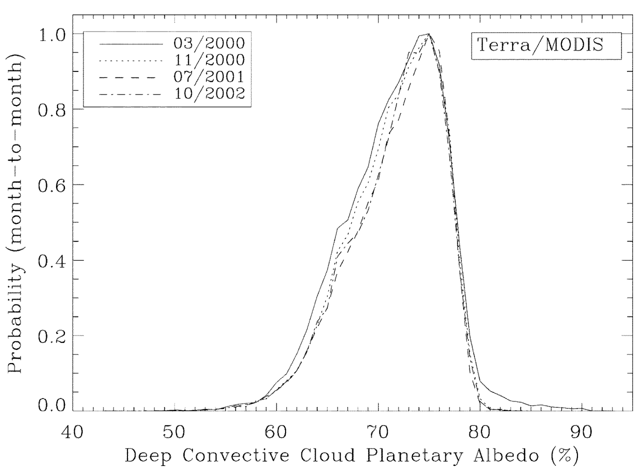

Fig. 8. MODIS stability studies using monthly broadband albedo distributions derived from narrowband-to-broadband conversions using MODIS narrowband observations as inputs.

conversion as well as uncertainties in anisotropy. The albedo distributions for all other months (not shown here) are quite similar and with the same shapes, and the peaks are within a couple of percent. It implies that both VIRS and MODIS calibrations have been consistent over time, and the instruments are stable.

VI. Summary

This paper identified the coldest and thickest clouds for the purpose of monitoring instrument stability and assessing cloud absorption anomaly. With proper cloud-top temperature (Tc $<$ 205 K) and optical depth ($>$ 40) criteria, we are able to single out the cold opaque deep convective clouds with planetary albedos of 0.75 and the remaining 25% of solar radiation absorbed by these clouds. The present results shown that the 25% of observed deep convective cloud absorption is 7% higher than model calculations if we assume the effective diameter of the ice cloud particles is around 30 m. The absorption discrepancy between model and observations reduces if the effective particles are larger. The magnitude of the discrepancy can be accurately assessed with cloud microphysics measurements from CRYSTAL-FACE. These deep clouds are excellent targets for monitoring instrument stability because their albedos are high and do not vary from month to month. The aerosols and trace gases contribute little to the albedos of these clouds and do not cause significant monthly variations.

A comparison of monthly deep convective cloud planetary albedo distributions from broadband observations made by the CERES instrument on TRMM reveals that the peak albedos are always around 0.75 and the shapes of the distributions are exactly the same during the entire TRMM/CERES period. It indicates that TRMM/CERES instrument has been well calibrated, and the shortwave channel has been very stable.

A nonlinear regression neural network narrowband–broadband conversion method is established for studying narrowband instrument stability. First, a narrowband reflectance is converted to broadband reflectance using the neural network conversion model. Then, the broadband albedo is derived using CERES anisotropy information. The neural network conversion model is trained with collocated CERES–VIRS reflectance pairs. Similar to the ones from broadband observations, the deep convective cloud broadband albedo distributions derived from narrowband reflectances can be used for narrowband instrument stability monitoring. Applying the neural network conversion method, the deep convective cloud broadband albedo distributions are derived from VIRS and MODIS narrowband observations. Although the shape of distributions is slightly different from that of CERES broadband measurements, the month-to-month albedo distribution variations are within 1%. Both VIRS and MODIS have been very stable.

A similar analysis has been done on the observations made by CERES on the Terra satellite, and the same conclusion also applies to the Terra/CERES instruments for the entire Terra/CERES measurements.

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